Cryogenic Selective Surfaces

Robert Youngquist and Mark Nurge, KSC, NASA

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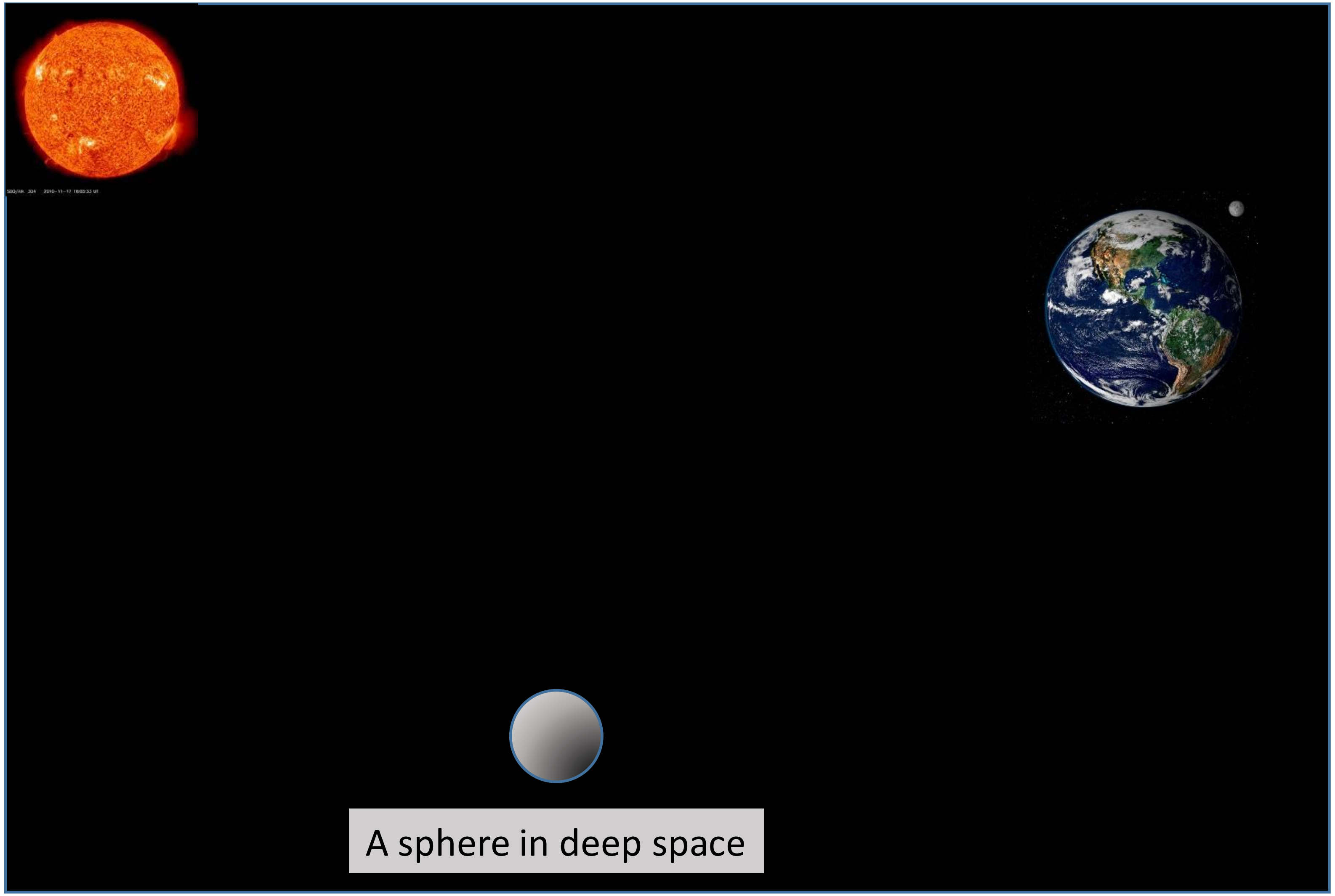

If we place a sphere in deep space at 1 AU from the sun, what will it's temperature be, assuming it absorbs radiation from the sun and emits infrared radiation in all directions?

Our goal is to find a way to make this sphere as cold as possible.

Hopefully cold enough to store liquid oxygen (90 K) or operate superconductors (77 K).

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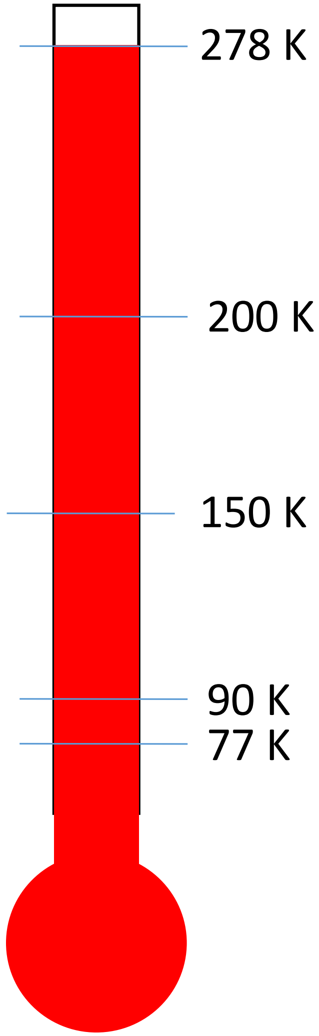
<u>What if we paint the sphere black?</u>

In other words, what if it absorbs all of the sun's energy?
(This is about 1363 Watts/m^2).

If it is a good absorber, it is also a good emitter of energy and can be treated as a blackbody. So we just have to solve

$$1363\mathrm{W/m}^2(\pi r^2) = \sigma(4\pi r^2)T^4$$

Where σ is the Stefan Boltzmann constant = 5.67x10^{-8} W/(m^2-K^4).
This yields 278 K, about 41 ^{o}F, so let's call that our starting point.



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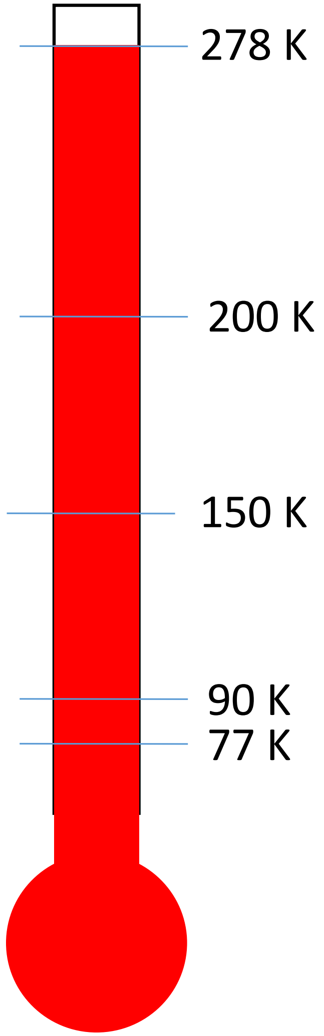
What if we polish the sphere so it is highly reflective?
For example, what if it absorbs only 5 % of the sun's energy?

If it is a poor absorber, it is also a poor emitter of energy and can be treated as a grey-body. So we solve

$$(0.05)1363\mathrm{W/m}^2(\pi r^2) = (0.05)\sigma(4\pi r^2)T^4$$

The 0.05 factors cancel and we still get 278 K, so that didn't help.

The Earth is approximately a spherical grey-body. But the Earth's average temperature is a little warmer, 58 °F , because of greenhouse effects and internal heating.



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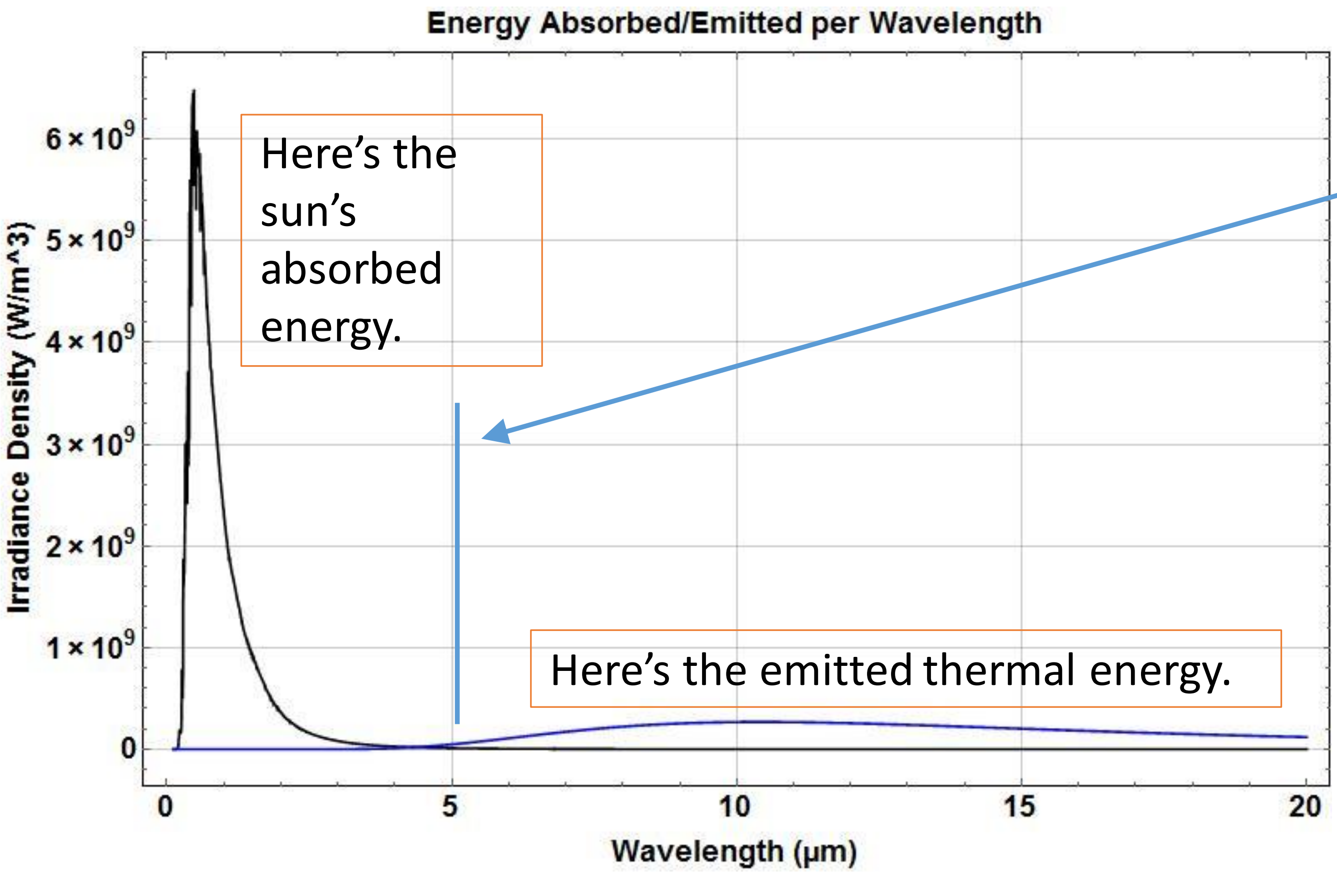
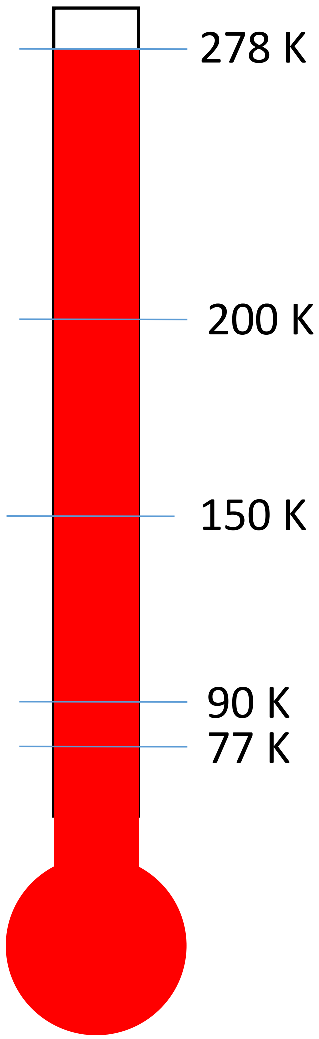
So consider this more carefully.



If we could reflect all energy below this line (about 99% of the sun's energy is below 5 microns) and not affect the infrared emission the sphere would reach 77 K.

How do we do that?



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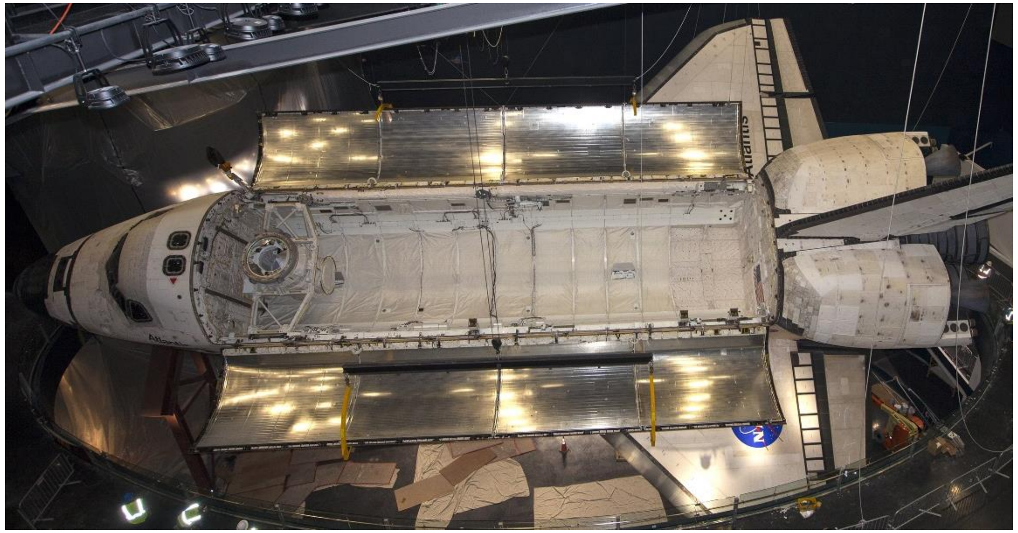
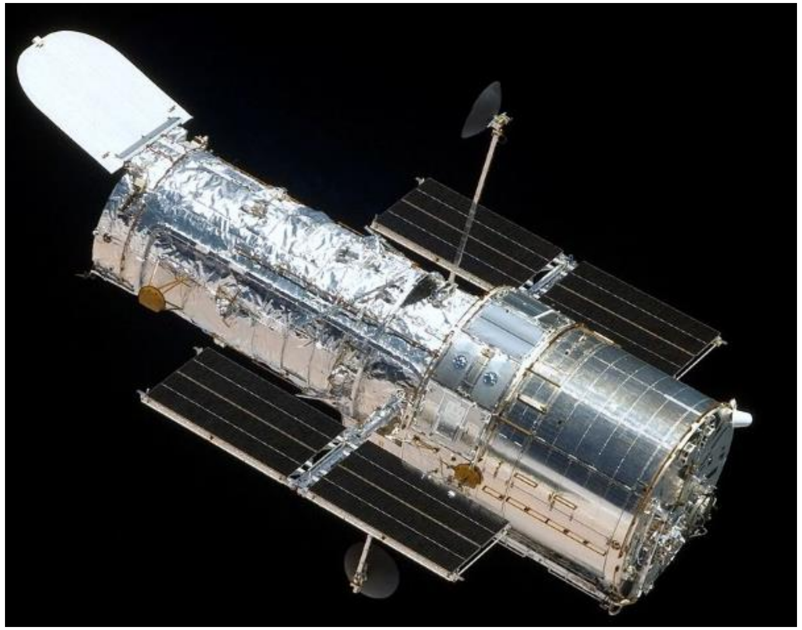
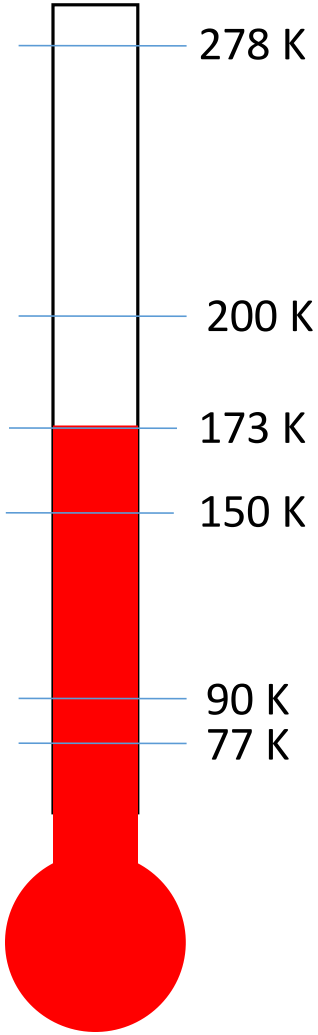
One approach is second surface mirrors. Coat the sphere to make it reflective and then place a layer over that coating which is transparent at short wavelengths and black at long wavelengths.

The Space Shuttle Orbiter payload bay doors and the Hubble Space Telescope both use this approach.







Both use transparent plastic with aluminum/silver. Roughly 90% of the sun's energy is reflected. If we place this coating on our sphere its temperature will drop to 173 K.

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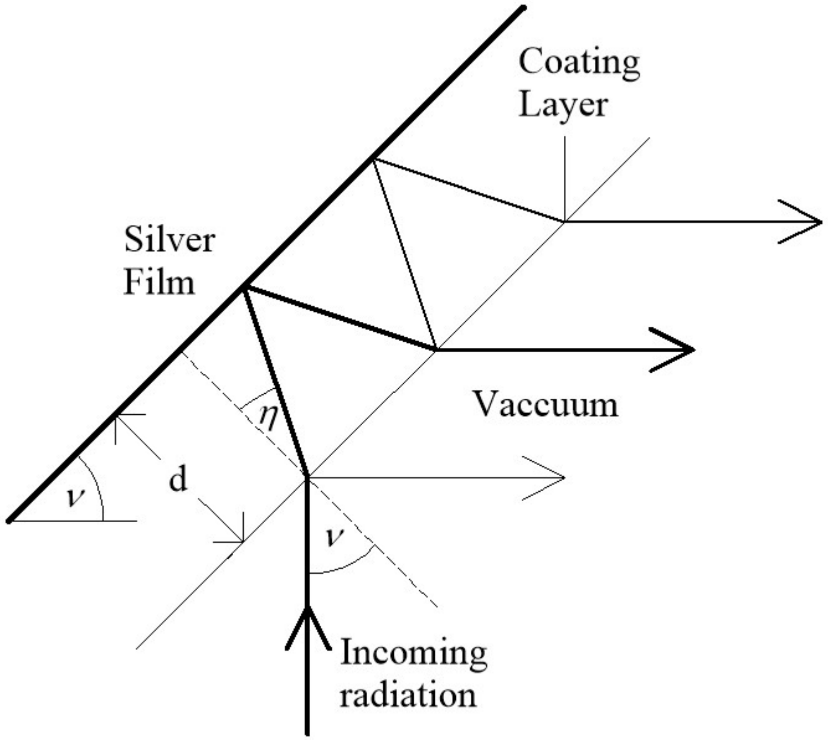
But we need to do better, so we decided to model silver on sapphire. Silver is the optimal metallic reflector and sapphire has a 5-7 micron transition region, better than plastic.



We used the fully complex form of the Fresnel Equations to model the interaction of the sun's irradiance with the second surface mirror.

$$R_{SN}[\eta,\lambda]=\left[\frac{(n[\lambda]+i\kappa[\lambda])\cos[\eta]-(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}{(n[\lambda]+i\kappa[\lambda])\cos[\eta]+(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}\right]\left[\frac{(n[\lambda]+i\kappa[\lambda])\cos[\eta]-(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}{(n[\lambda]+i\kappa[\lambda])\cos[\eta]+(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}\right]^*$$

and incorporate a multi-reflection model to obtain the wavelength dependent absorption.

$$\boxed{A_N[\nu,\lambda]=\frac{T_N[\nu,\lambda](1-T_C[\nu,\lambda]^2R_{SN}[\eta,\lambda])}{1-T_C[\nu,\lambda]^2R_{SN}[\eta,\lambda]R_N[\nu,\lambda]}=\frac{(1-R_N[\nu,\lambda])(1-T_C[\nu,\lambda]^2R_{SN}[\eta,\lambda])}{1-T_C[\nu,\lambda]^2R_{SN}[\eta,\lambda]R_N[\nu,\lambda]}}$$

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Then we integrate the absorption over the sun's irradiance to find absorption as a function of angle

$$A_{tot}[\nu]=\cos[\nu]\int I_s[\lambda]A[\nu,\lambda]d\lambda=(\cos[\nu]/2)\int I_s[\lambda](A_P[\nu,\lambda]+A_N[\nu,\lambda])d\lambda$$

We equate absorption with emission and use the Plank distribution to find the emitted energy as a function of temperature

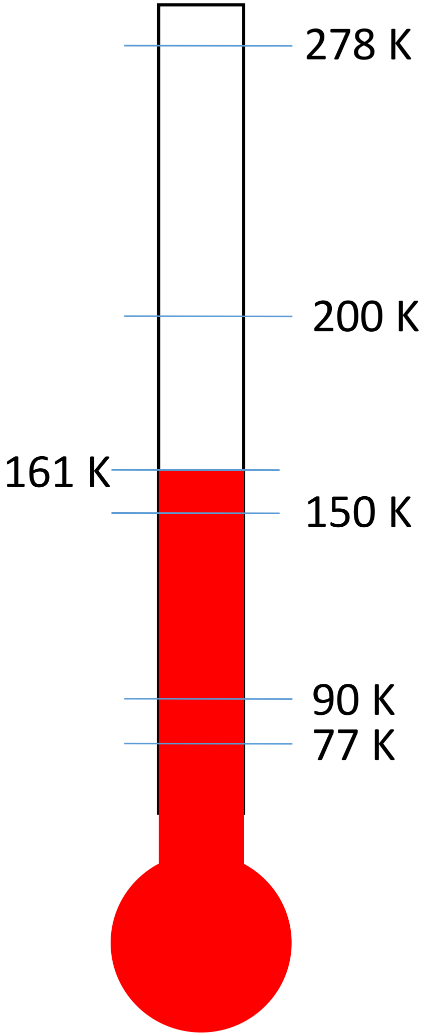
$$P[T]=2\pi\int_0^{\infty}\int_0^{\pi/2}\frac{2hc^2}{\lambda^5}\frac{A[\theta,\lambda]}{\exp[\frac{hc}{\lambda kT}]-1}\cos[\theta]\sin[\theta]d\theta d\lambda$$

We finally integrate the absorption over the sphere, accounting for angle, and set the emitted energy equal to the absorbed energy to find the temperature of the sphere.

$$P[T]4\pi R^2=\int_0^{2\pi}\int_0^{\pi/2}A_{tot}[\nu]R^2\sin[\nu]d\nu d\phi=2\pi R^2\int_0^{\pi/2}A_{tot}[\nu]\sin[\nu]d\nu$$

After 2 hours of computer time, the result, for an optimal 0.2 mm sapphire thickness, is 161 K.

Not much of an improvement.



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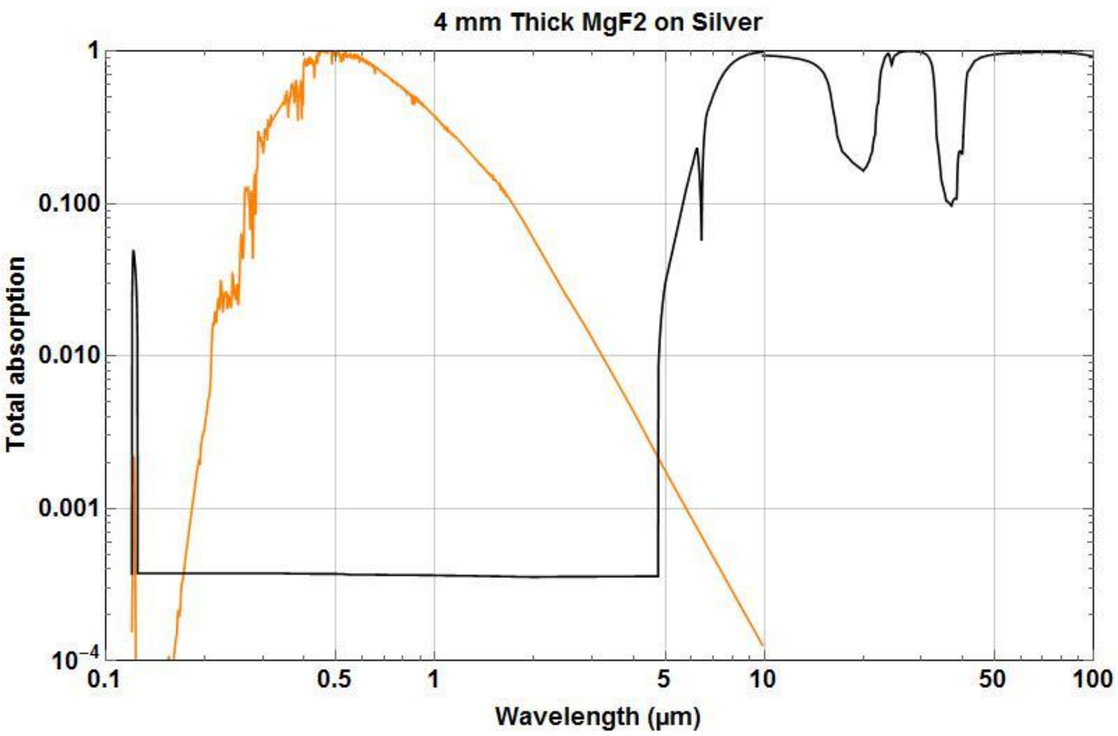
That's not good enough, so we decided to model silver on CaF_2 and MgF_2.



This is the absorption spectrum of a 4 mm thick piece of MgF_2 with a scaled solar spectrum. Note that most of the sun's energy passes through MgF_2.

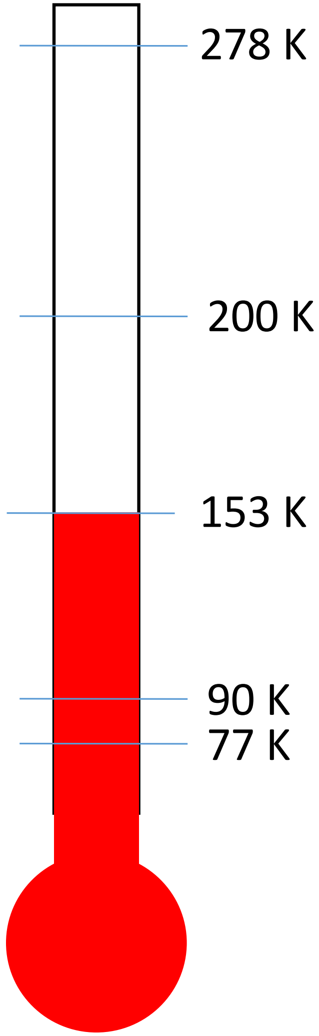
We went through the model process for each of these two materials and obtained lowest temperatures of

156 K for 2 mm of CaF_2

And

153 K for 4 mm of MgF_2.

Better, but not good enough.



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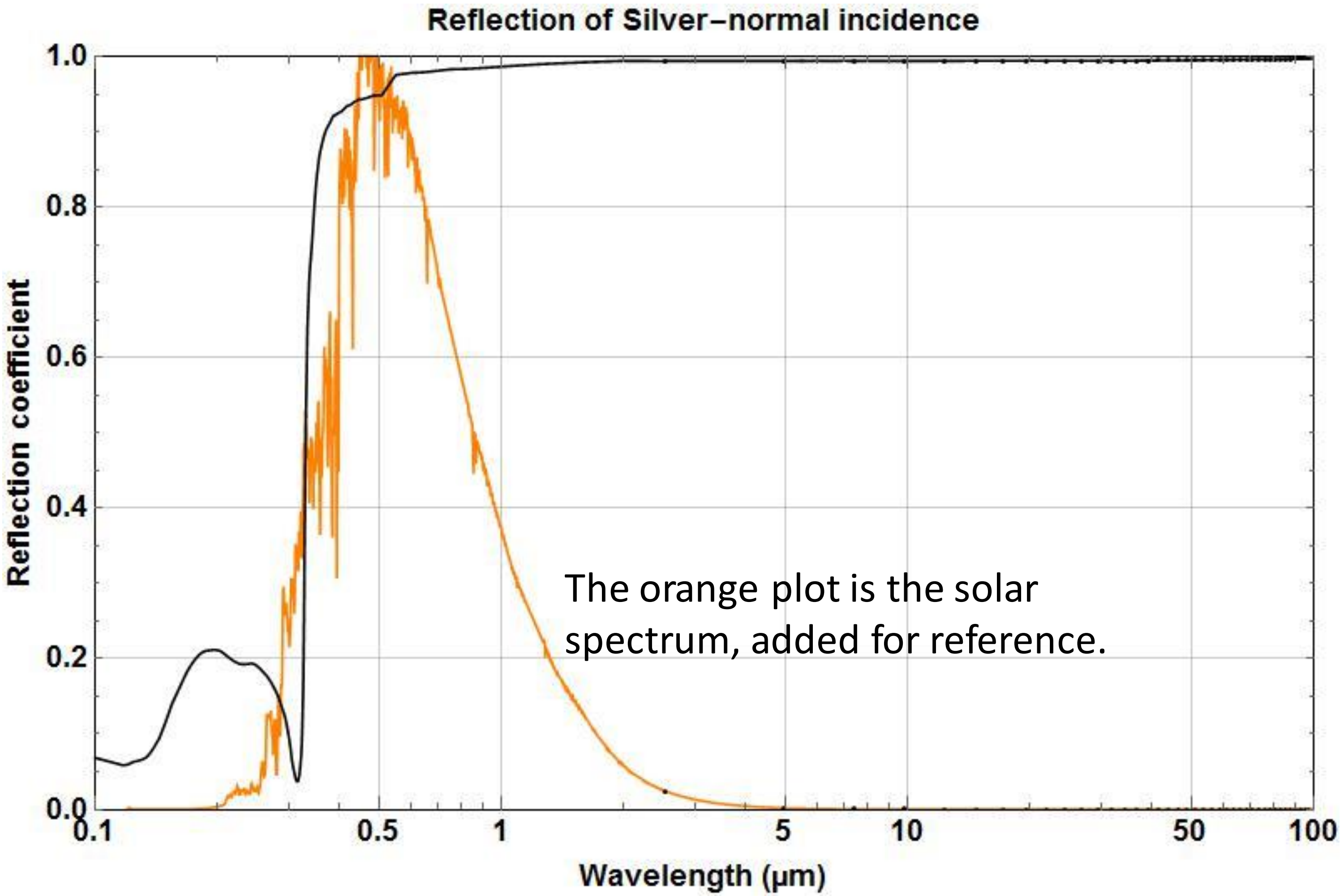
The problem is in the silver.



Silver doesn't have a high enough reflection coefficient in the visible and absorbs significant solar energy in the 300 nm region (ultraviolet).

So second surface mirrors will not achieve cryogenic temperatures.

We need another approach.

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This ultra-broadband dielectric mirror from Newport has better than 99% reflectivity from 350 nm to 1100 nm and from 0-50 degrees angle. Part No. 10Q20BB.3

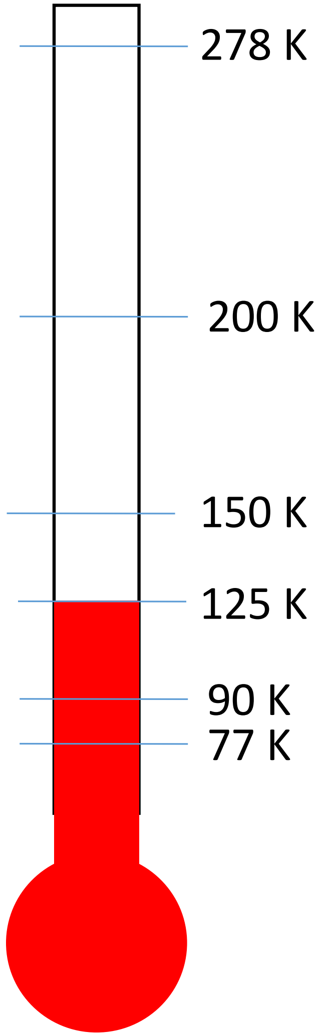
How about Dielectric Mirrors?

We contacted Newport Thin Film Laboratory and Reynard Corporation and gave them our requirements (99% solar reflection).

Newport suggested a design, but it had far too much infrared absorption.

The Reynard rep. said “I don’t think 98% is possible in two years.”

This is an advancing area, but we can’t count on a breakthrough. If we assume 96% reflectivity we only reach 125 K. Not good enough.



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I was on the verge of giving up, when one morning inspiration hit me.

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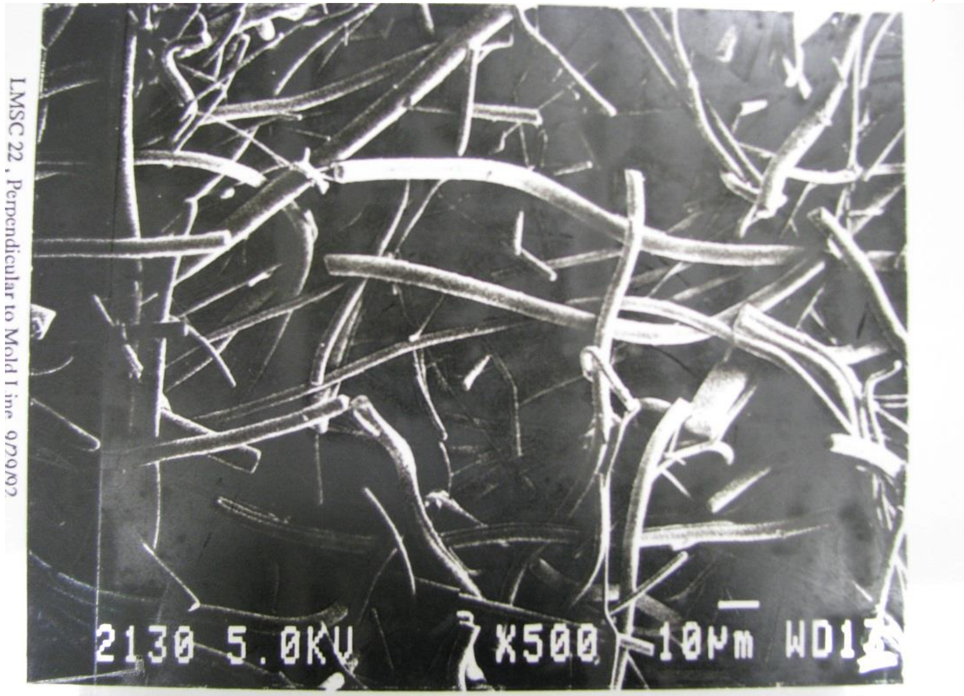
This is a 2 inch cube of Shuttle tile material.

It is composed of nearly pure glass which has essentially no absorption in the visible spectrum.



This is an SEM image of the tile, showing the glass fibers that make up about 6% of its volume.

So what happens when light hits this tile sample?

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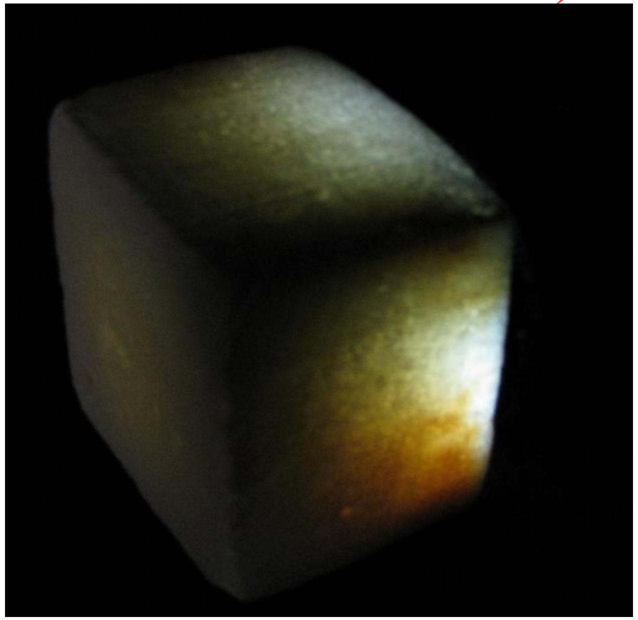
When the tile is illuminated the light is scattered back. In this photo of a flashlight illuminating the tile sample the camera is saturated.



This picture was taken with the flashlight pressed against the tile and the room lights turned off. Minimal light reaches the back of the tile, and since the glass cannot absorb the light, it all must be scattering from the front.

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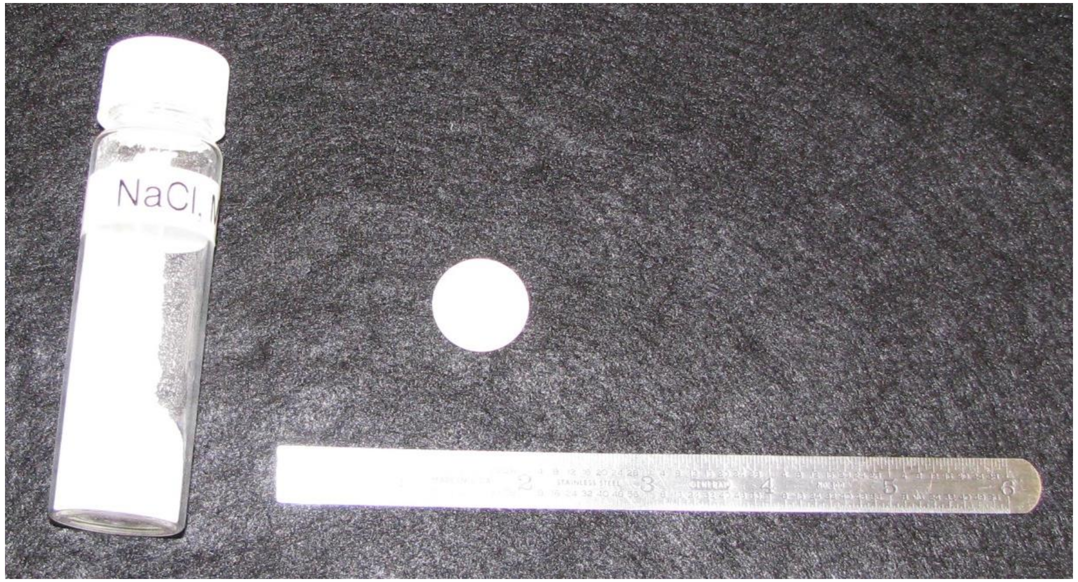
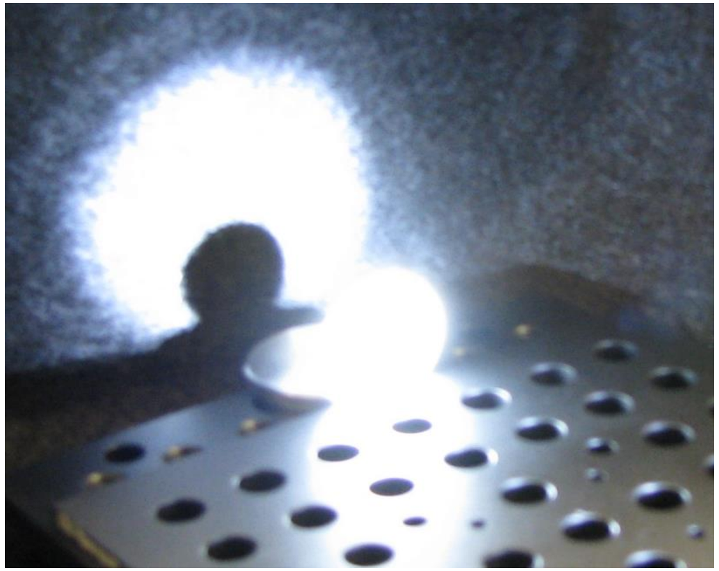
The glass tile reflects back nearly all of the visible light that hits it!

What if we could make a similar structure from a solar transparent material like CaF_2, MgF_2, BaF_2, or NaCl? Can we scatter most of the solar spectrum back out the front of the material?





We ground NaCl into a fine powder and made a small disk (20 mm diameter, 1.1 mm thick) in a press. It performed well at stopping light, even though it has no visible absorption.

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So if the material is transparent to the entire solar spectrum it will be truly "white", i.e. **"Solar White".**

Titanium Dioxide Powder-0.25 micron transparent particles used to make things white, including paint, cottage cheese, skim milk, toothpaste, some cheeses and ice creams, etc. .

We studied Radiation Transfer Theory and developed both discrete and continuous functional solutions to model the scattering of light in an isotropic homogeneous material.

Our models were evolving nicely, when one day we predicted that white paint shouldn't exist, in that we could not achieve in our models the performance achieved by commonly used white paint. So we began to study white paint and found that most white paint is composed of Titanium Dioxide particles (DuPont) in a binder. Studying this we found that the optimal size for the particles is about 0.25 micron diameter. This provides a scattering enhancement in the visible of about 4 and, due to the small particle size, allows thin films to be generated.

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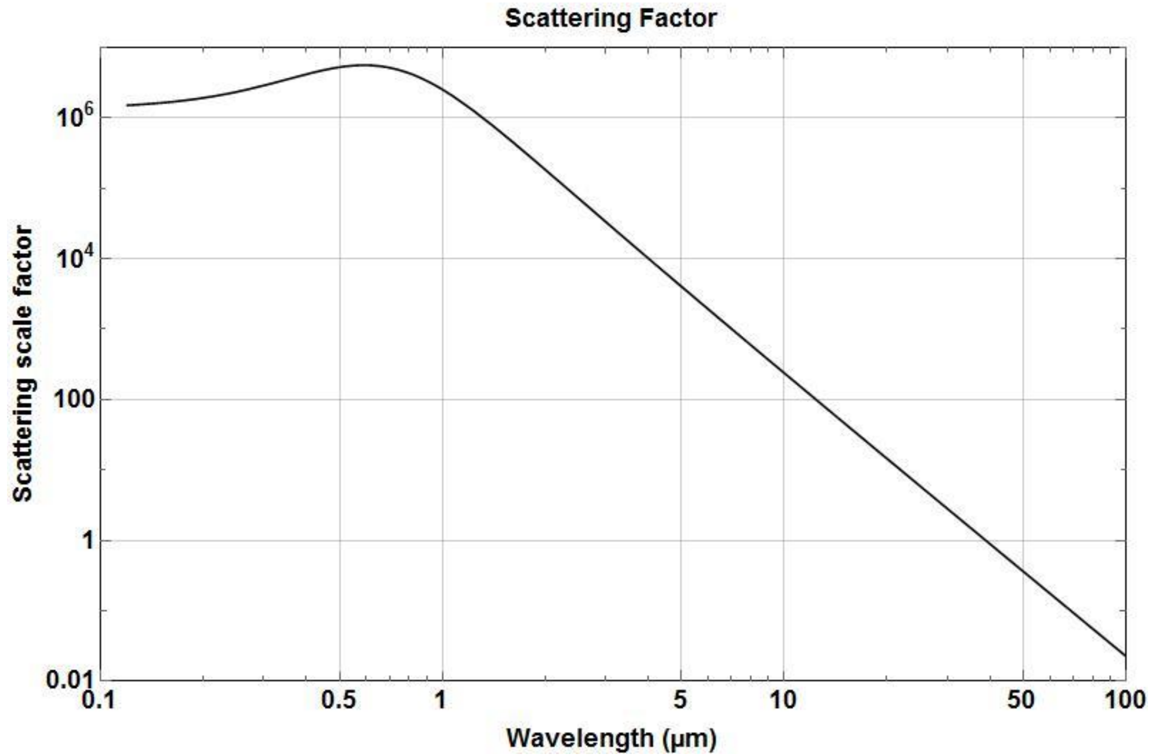
Since scattering is wavelength dependent we incorporated a Mie Scattering effect into the model. We chose to place the diffuse coating on top of a layer of silver, so that at long wavelengths, where the radiation no longer "sees" the scattering particles, the silver will take over as the reflecting agent.



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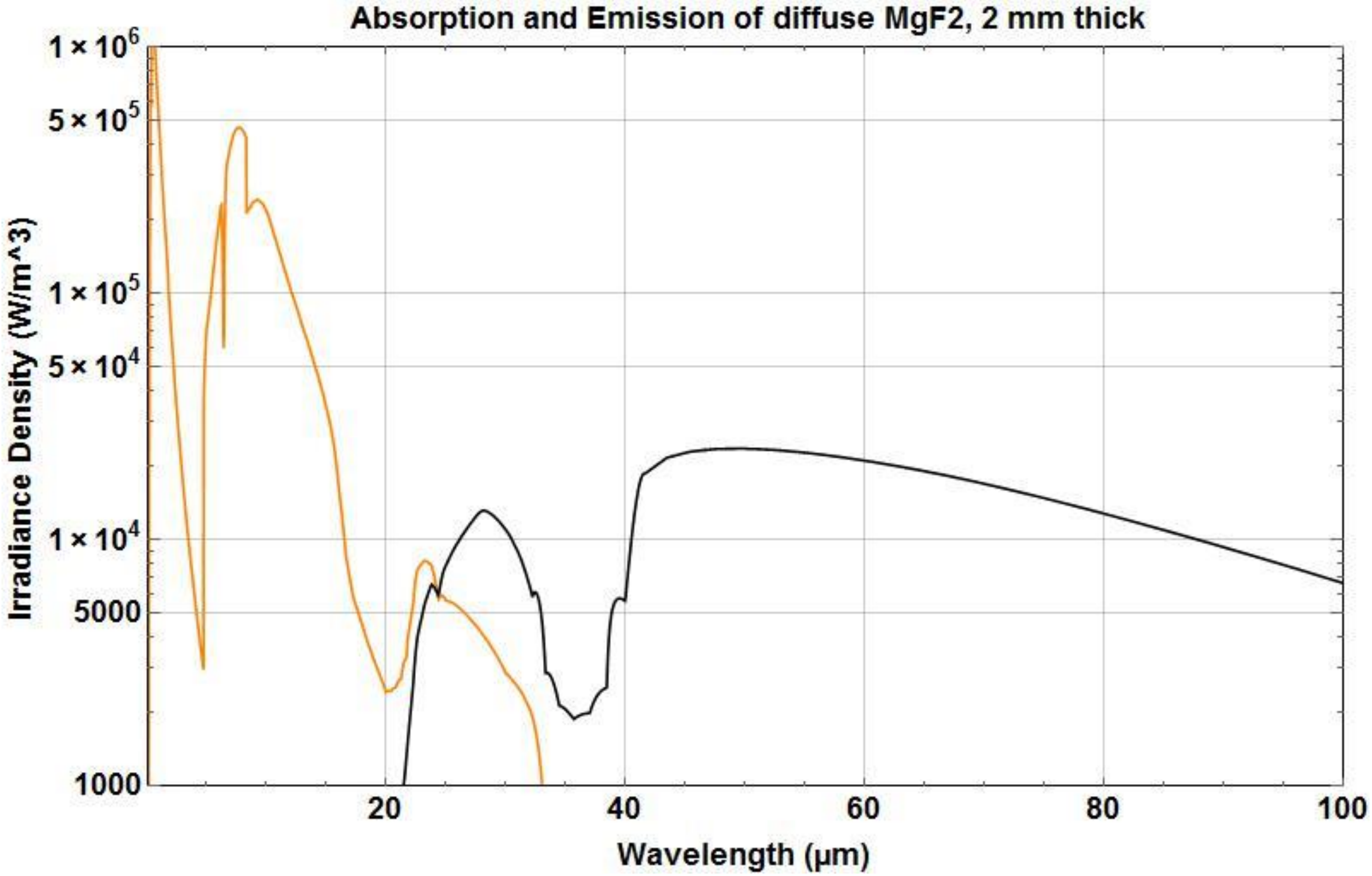
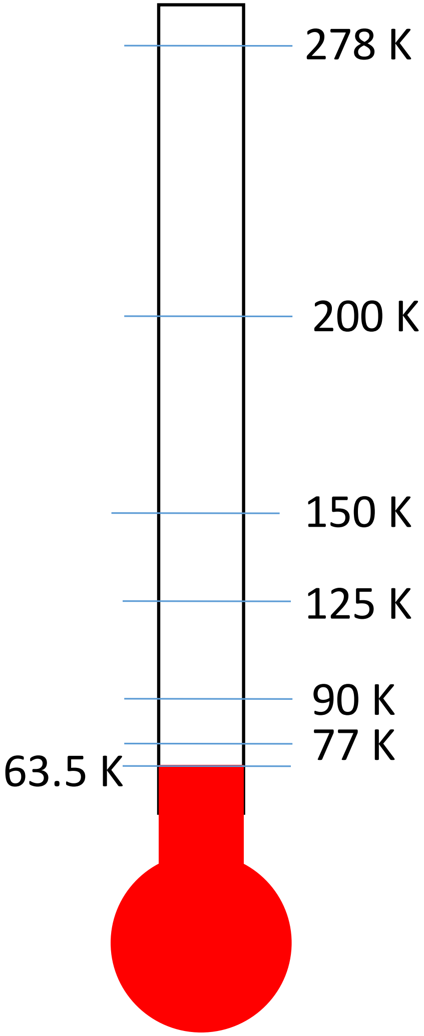
After several hours of computer time we obtained this absorption and emission curve for 2 mm of MgF_2. Only 2.55 Watts of solar energy are absorbed!! Less than 0.2% of the solar energy! We have achieved cryogenic temperatures!!



63.5 K !!



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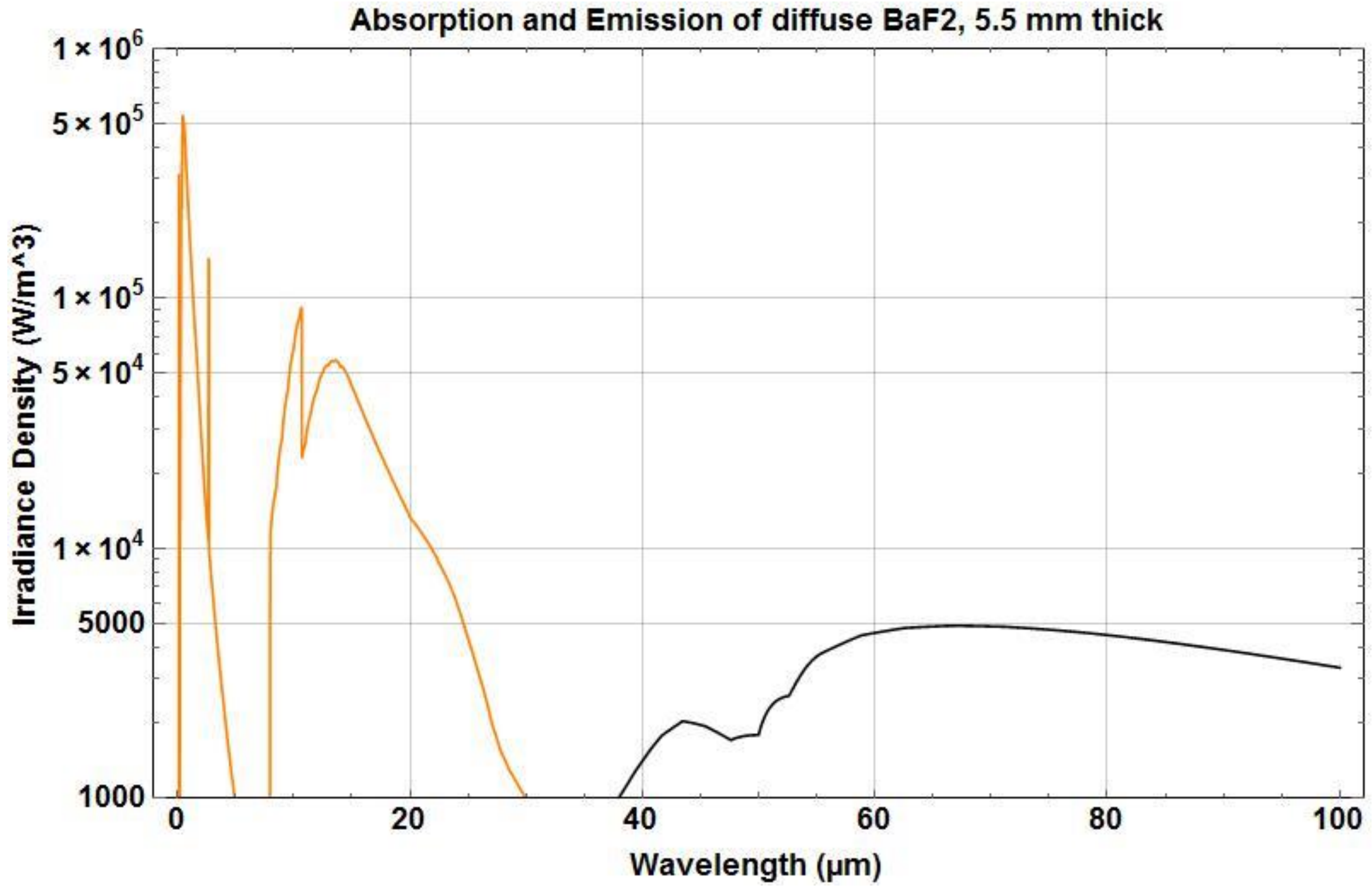
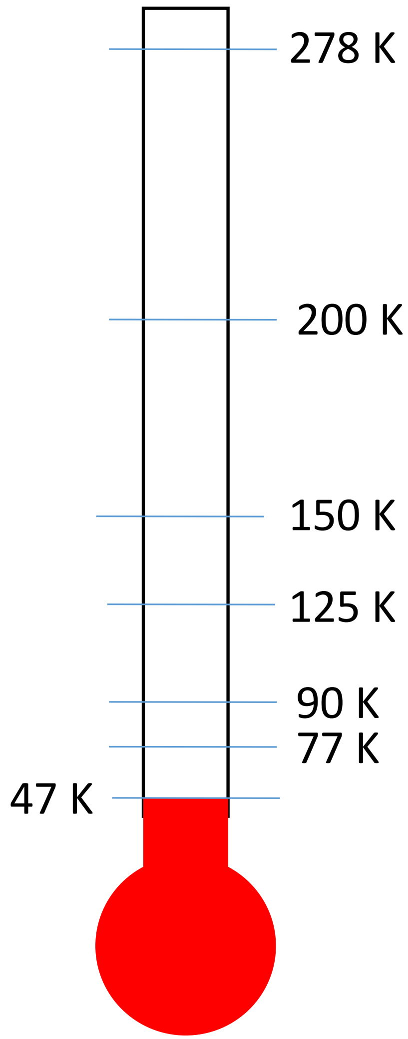
But we can do better. BaF2 better matches the sun's spectrum, reducing the IR absorption. A diffuse 5.5 mm coating of it, over silver, only absorbs 0.76 Watts of solar energy, less than 0.06%!



47 K !!

The freezing point of LOX is about 50 K



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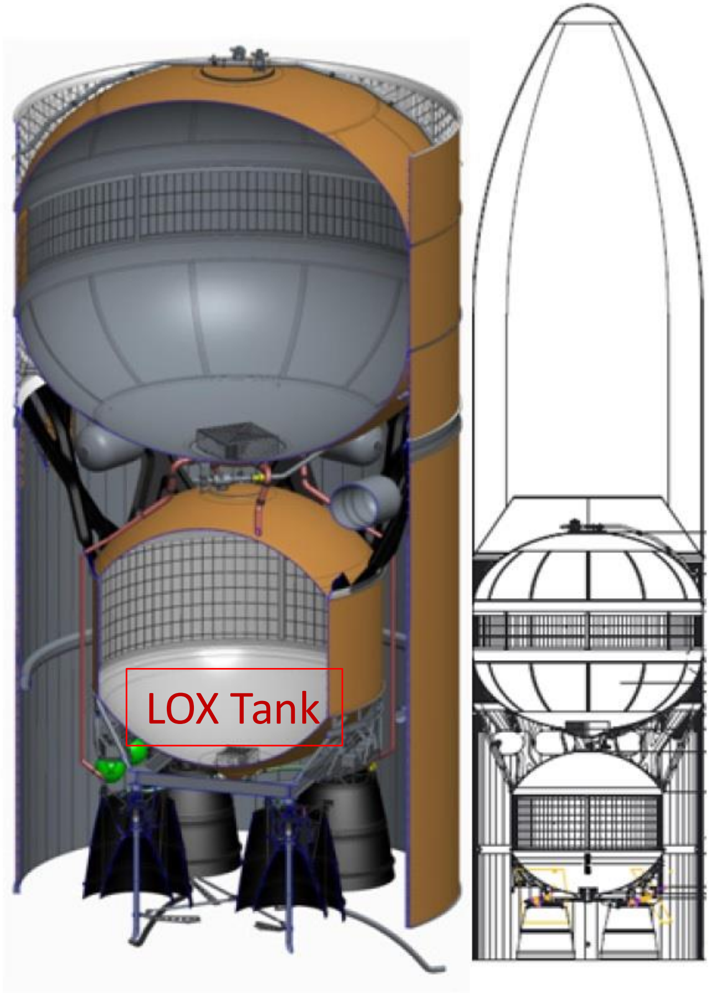
So what's next?

The aerospace goal is to design a LOX tank that will maintain the LOX on a trip to Mars, even in the presence of the sun.

But coating the tank is not enough. Most of the heat enters the tank through conduction along struts from 300 K objects and by 300 K thermal radiation.

We will utilize our new coating to coat the tank and struts, as well as consider radiative shielding, to try and arrive at a design that will minimize or eliminate the boil-off of LOX.

We've found that a diffuse coating of NaCl may help reflect 300 K radiation.



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Solar White Selective Surfaces—Potential Uses.

Better Radiators

Superconducting magnets

Better Heat Shields

Superconducting energy storage

LOX storage on the moon

Superconducting magnetic radiation shielding.

Liquid Air Tanks in Space.

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In Closing:

We are excited by this new “Solar White” coating and the possibilities it represents.

We have filed a provisional patent on this novel concept.

We have obtained internal (KSC) funding to start considering methods of fabricating this new diffusive coating.